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Modified water-cement ratio rule for the design of air-entrained concrete

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Keywords: Modified C/W; the volume of air entrained; cement consumption; strength and frost resistance of concrete; pore volume of aggregate; composition of lightweight concrete.

Abstract. Designing concrete compositions, containing entrained air, is usually done by means of empirical proportioning, which is quite a laborious and lengthy process. In the article design formulae are experimentally justified with rule of modified C/W, which is complex due to known empirical dependencies, and allow us to find the content of concrete components with desired strength, frost resistance, and density properties. Conducted experimental studies are: compression method for determining the volume of entrained air as well as standard methods for determining the strength and frost resistance of concrete. Lastly, generated formula was verified on an example for calculating the compositions of heavy concrete with a given strength and frost resistance and structural claydite-concrete with desired strength and density.

1. Introduction

One of the fundamental fields in concrete science is methodology of concrete compositions design, aimed at achieving concrete with a set of desired properties.

D. Abrams has for the first time proposed two approaches [1] for concrete compositions design: a so-called 'trial method' or experimental proportioning and a «preliminary calculations method» and considered that both approaches should be based on a water-cement ratio rule (low). Practice has confirmed this condition proved by Abrams however many subsequent researches have shown [2–5] that Abrams's statement that concrete strength for given materials and their processing conditions is defined just by the ratio between the water and cement volumes, used for manufacturing the concrete mixture' is some exaggeration and the word 'just' should be replaced by 'mainly' or 'basically'. In addition to the water-cement – W/C (or cement-water – C/W) ratio and cement strength or its activity (R_{cem}), in calculating the concrete composition it is necessary to take into account additional factors affecting the properties of concrete.

In 1920, having processed more than 50000 tests, Abrams proposed an empirical formula:

$$f_{cm} = \frac{k}{A^X}, \tag{1}$$

where k and A are coefficients;

X is the water to cement volume ratio for cement with a density of 1500 kg/m^3.

Many studies were carried out to specify the water-cement ratio rule and increase the number of factors, considered in equations for predicting concrete strength [6–12]. The most important investigations in this field

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are based on structural approach. In these studies the initial preconditions are based on hypotheses of interrelation of concrete strength and its structure, though these hypotheses are essentially different.

There is a number of design equations for concrete strength, trying to consider the complex interaction mechanism between aggregates and cement matrix at heterogeneous material's collapse [1, 6, 13]. These equations represent a big interest to studying possibilities of predicting concrete strength variation due to changes in strength and deformation characteristics of phases composing the material. However, at present time using these equations for concrete compositions design is usually inconvenient or impossible.

An attempt to increase the number of factors, considered in concrete compositions design and to consider the influence of aggregates features resulted in the «real» W/C theory [6] $(W/C)_r$:

$$\left(W/C\right)_r = \frac{W - W_S S - W_{cr.s} Cr.S}{C}, \tag{2}$$

where W and C are total content of water and cement; W_s and $W_{cr.s}$ are water demand of fine and coarse aggregates; S and $Cr.S$ are mass content of fine and coarse aggregates respectively.

Water demand parameters of fine and coarse aggregates characterize the water quantity that should be added to cement paste per unit of its mass in order to obtain a corresponding mortar mixture with C:S (cement:sand) = 1:2 composition or a concrete mixture with C:S:Cr.S (cement:sand:crushed stone) = 1:2:3.5 composition, having the same slump after mixing as cement paste with normal consistency [6].

In opinion of some researchers [6], "real" W/C characterizes the cement paste in concrete after immobilization of water by the aggregates through a certain structure formation period. In our opinion «real» W/C can be interpreted as W/C of cement paste in concrete mixture at the moment of equal moisture carrying potentials.

Using the $(W/C)_r$ concept for concrete with constant entire W/C value enabled to estimate the dependence of concrete strength on some factors that affect redistribution of water between the cement paste and aggregates. At the same time the algorithm of using $(W/C)_r$ in the concrete design is complex and requires additional assumptions.

Great opportunities to take into account various factors affecting the properties of concrete when design the its composition open experimental models obtained using statistical methods for the processing of experimental data [14–24]. However these models are usually local and fair under the specified conditions of the experiments.

Presently for predicting concrete strength and for concrete composition design the following typical formula is widely used [1]:

$$f_{cm} = AR_{cem}(C/W - b), \tag{3}$$

where f_{cm} is the concrete strength at 28 days;

C and W are the masses of cement and water per 1 m^3 of the concrete mix;

A and b are empiric coefficients, depending on the initial materials features and structural type of concrete; R_{cem} is the compressive cement strength at 28 days.

Still Bolomey has mentioned that linear formula for prediction concrete strength $f_{cm} = k(C/W - 0.5)$ is valid just if C/W = 0.9...2.5 [1]. For wider diapason a nonlinear version of the formula was proposed. The general nonlinear function $f_{cm} = f(C/W)$ is often replaced in practice with linear piecewise dependences, proposed and proved by B. Skramtaev and Y. Bazhenov [1]. Alongside with Eq. (3) a number of other formulas, based on a water-cement rule are known (Table 1). They, however, are almost not applied because a relatively more complex structure and necessity of additional data. Another reason for limited use of these formulas is lack of essential increase in prediction accuracy.

It is more convenient to consider the factors, along with C/W, which significantly affect the strength of concrete, the system of amendments ΔAi for the coefficient A in formula (3). Such a system was developed by V. Sizov [1].

A number of computational and experimental dependencies [12, 24–27] were proposed to take into account the characteristics of aggregates and additives in the designation of concrete compositions.

Table 1. Main design formulas for predicting concrete strength, used for concrete compositions design [1].

Authors	Relation for strength prediction	Notations
R. Feret	$f_{cm}=k\left(\frac{V_{cem}}{V_{cem}+V_w+V_{air}}\right)^2$ (4)	V_{cem} – absolute cement volume, V_w – water volume, V_{air} – volume of air voids in concrete,
N. Belyaev	$f_{cm}=\frac{R_{cem}}{A(W/C)^{3/2}}$ (5)	k – coefficient, depending on materials quality, used for concrete, manufacturing and curing conditions, R_{cem} – ultimate cement strength
American Concrete Institute Manual of Concrete Practice [8]	$f_{cm}=117.07e^{-2.572W/C}$ (6)	$W/C=0.41-0.82$
B.Skramtaev, Y.Bazhenov	$f_{cm}=AR_{cem}\left(C/W-0.5\right)$ $for\ \mathrm{W}/C\geq 0.4,$ $f_{cm}=A_1R_{cem}\left(C/W+0.5\right)$ $for\ \mathrm{W}/C<0.4$ (7)	
M. Simonov	$f_{cm}=0.49AR_{cem}\left(\frac{3.1C/W}{3.1+C/W}\right)^2$ (8)	A – coefficient, depending on aggregates quality.
L.Kaiser, R.Chehova	$f_{cm}=\frac{\left(2.3\,R_{cem}+100\right)\,\mathrm{C}/W-80}{10}$ (9)	
I.Rybiev	$f_{cm}=\frac{R^*}{\left(\frac{W/C}{(W/C)^*}\right)^n}$ (10)	$(W/C)^*$ – water-cement ratio of maximum possible cement stone strength, R^* – maximum possible cement stone strength, n – coefficient, depending on features of concrete macrostructure and applied aggregates.
I.Ahverdov	$f_{cm}=\frac{KR_{cem}}{0.95\frac{1+1.65K_{n.c}}{K_{n.c}}\left(W/C\right)-1.65K_{n.c}}$ (11)	$K_{n.c}$ – normal consistency of cement paste.
V.Shmigalsky	$f_{cm}=R_{cem}\frac{0.6-0.0014W}{\left(W/C\right)^{1/3}}$ (12)	

To take into account the influence of mineral additives and the entrained air on the strength of concrete, it was suggested [1] to use the modified Bolomey formula:

$$f_{cm}=K_b\left(\frac{C+K_{c.e}Ad}{W+V_{air}}-0.5\right), \tag{13}$$

where f_{cm} is the compressive strength,

K_b is the constant of Bolomey,

C is mass of cement,

Ad is the mass of mineral additive,

W is the mass of used water,

V_{air} is the volume occupied by the entrained air equivalent the mass of water,

$K_{c.e.}$ is the coefficient of «cementing efficiency» or «cement equivalent» of 1 kg additive.

The formula (14) reflects a depending that can be considered the "*rule of modified W/C*" (or C/W). In accordance with this rule the strength of concrete additionally to the effect of the ratio of cement and water content by weight can be affected the ratio of equivalent amounts of active mineral additives and entrained air. The ratio of the total content of these components of concrete uniquely determines the strength of concrete.

Based on this rule, a number of studies of concrete compositions design with fly ash and other mineral additives were performed [1, 7, 25, 28, 29]. At the same time for concrete, containing entrained air, this rule, insufficiently experimentally substantiated.

The purpose of the research, the results of which are given in the article, was to determine the possibility the applicability of the calculated dependencies of concrete strength based on the modified C/W for design of concrete compositions take into account the volume of air entrained by the addition of the surface-active substances (SAS) and porous aggregates.

2. Methods

As an air-entraining additive was used air-entraining resin (neutralized Vinsol) – a product of neutralization of the wood resin by caustic soda after extraction of turpentine from it. The additive introduced into concrete mixtures in an amount of 0.01...0.03 % by weight of cement, previously dissolved in water at t = 30...40 °C. The volume of entrained air in concrete mixtures was determined by compression method based on the law Boyle-Marriott, establishing the relationship between the volume of air and the applied pressure at a constant temperature (EN 206-1).

For the manufacture of concrete mixtures used Portland cement CEM II/ A-S with the mineralogical composition of clinker, %: C_3S – 57.10; C_2S – 21.27; C_3A – 6.87; C_4AF – 12.9. Specific surface of cement – 340 m^2/kg. The compressive strength of cement corresponded to the class of 42.5 N (EN 197-1). Fine aggregate of concrete served the quartz sand with a modulus of fineness M_k = 1.95 and a content of dust and clay impurities of 2.1 %. As a coarse aggregate of the normal weight concrete, granite crushed stone of fraction 5...20 mm was used, light concrete – claydite gravel of fraction 5...20 mm with bulk density of 500...800 kg/m^3.

Testing the strength of concrete was carried out on control samples-cubes with a fin length of 100 mm in accordance with GOST 10180-2012 (EN 12390-3:2009).

The frost resistance of concrete was determined by the ultrasonic method (Russian State standard GOST 26134-2016). The tests are carried out until the “ultrasound-velocity-number of cycles” line will break, after that the reduction in ultrasound velocity will have higher intensify.

Experimental researches were carried out in the research laboratory of the building materials tests of the National University of Water Environmental Engineering (Ukraine, Rovno).

3. Experimental results and discussion

Concrete with entrained air. When calculating the compositions of concrete with entrained air, the formula (13) with Ad = 0 can be brought to mind:

$$f_{cm} = AR_{cem}\left(\frac{C}{W+V_{air}} - 0.5\right), \tag{14}$$

were A is coefficient taking into account the quality of raw materials [1];

R_{cem} is compressive strength of cement, MPa;

C and W is cement and water consumption in concrete mix by weight, kg/m^3;

V_{air} is the volume of entrained air V_{air}, l/m^3.

An analysis of the effect of the volume of entrained air on formula (15) on the strength of concrete for various values of C/W and W is shown in Figure1.

On average, the calculated decrease in concrete strength for each percentage of air involved is 3.5...4.5 %. A tendency to a decrease in the relative effect of entrained air on strength is observed at C/W = const with an increase in water consumption in concrete. The calculated data are close to experimental (Figure 1).

The main purpose of air-entraining additives in concrete is to increase its frost resistance by creating a system of uniformly distributed closed air pores. This fact has been convincingly proved by the practice of construction and numerous studies. Processing our experimental data [1] included results of concrete frost resistance measurements in freezing cycles at –15...–20 °C and thawing at +15...±5 °C until strength decreases no more than 5 % for a rather wide compositions diapason ($f_{cm}^{28} = 15...40$ MPa, $W = 140...220$ l/m^3, $V_{air} = 0.8...6.5$ %). The data are approximised by a formula that has the following type:

$$F = A_1 f_{cm}^{28A_2} \exp^{A_3 V_{air}}. \tag{15}$$

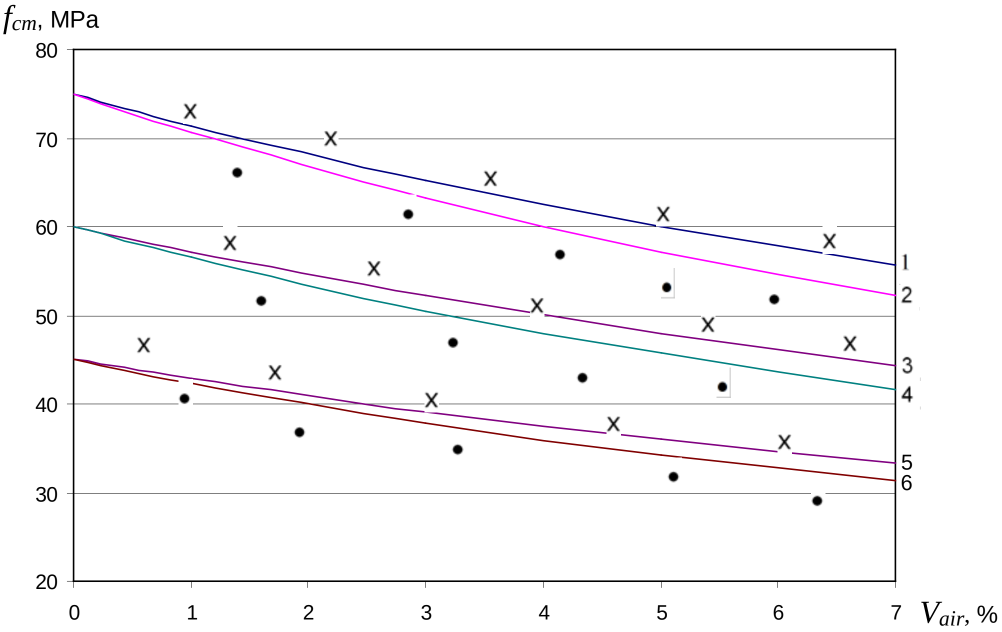

Figure 1. Influence of the volume of entrained on the concrete compressive strength 1 – C/W = 1.5; W = 200 l/m³. 2 – C/W = 1.5; W = 160 l/m³. 3 – C/W = 2; W = 200 l/m³. 4 – C/W = 2; W = 160 l/m³. 5 – C/W = 2.5; W = 200 l/m³. 6 – C/W = 2.5; W = 160 l/m³ (A = 0.6; R_{cem} = 50 MPa) Experimental results: x – W = 200 l/m³; • – W = 160 l/m³.

For the investigated concrete $A_3 = 0.35$, A_1 and A_2 are varied depending on the water demand and correspondingly mixtures workability (Table 2).

As it follows from analyzing Eq. (15), at entrained air content of 3…5 % the concrete frost resistance increases by 3…6 times (Figure 2). For concrete strength above 30…40 MPa the relative increase of critical number of freezing-thawing cycles, achieved by entraining air a little increases. It can be explained by higher influence of closed pores of contraction origin.

Table 2. Values of coefficients A_1 and A_2 in Eq. (16) for concrete mixtures with various workability.

Concrete mixtures workability	A_1	A_2
Plastic concrete mixtures (Slump Sl = 9…12 cm)	0.34	1.68
Low-plastic concrete mixtures (Slump Sl = 1…4 cm)	0.91	1.47
Non-plastic concrete mixtures	2.48	1.25

As the empirical data on the values of parameters A_1 and A_2 is accumulated, Eq. (15) can be widely used either for predicting frost resistance or for concrete compositions design.

The required entrained air volume in % can be found according to a formula, obtained from Eq. (15):

$$V_{air} = \frac{\ln\left(\dfrac{F}{A_1 f_{cm}^{A_2}}\right)}{0.35}. \tag{16}$$

At the same time when designing concrete compositions with an air-entraining additive at given values of its strength and frost resistance, along with a significant increase in the latter the necessity of certain overestimating of the given concrete strength, depending on the entrained air volume, should be considered (Figure 3). The overall positive effect of reducing the consumption of cement can be quite significant, especially in concrete with high values of frost resistance and a moderate normalized value of strength. From Figure 4, in particular, it follows that f_{cm} = 20 MPa and F200 are provided without the addition of entrained air at W/C = 0.5 (C/W = 2) with the introduction of entrained air – W/C = 0.62 (C/W = 1.61).

Using the formula (14) at the design stage of concrete compositions and having previously determined the water consumption by reference or laboratory data, it is possible to calculate C/W, V_{air} and C values to ensure the specified indicators of concrete strength and frost resistance. The consumptions of aggregates and their ratio are using known recommendations [1–6].

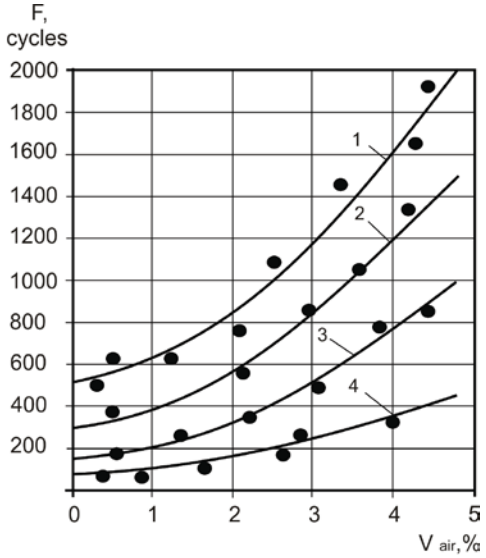

Figure 2. Affect of entrained air on concrete frost resistance (for concrete mixtures with Slump Sl = 1...4 cm) : *1* – $f_{cm}^{28} = 70$ MPa; *2* – $f_{cm}^{28} = 50$ MPa; *3* – $f_{cm}^{28} = 35$ MPa; *4* – $f_{cm}^{28} = 20$ MPa .

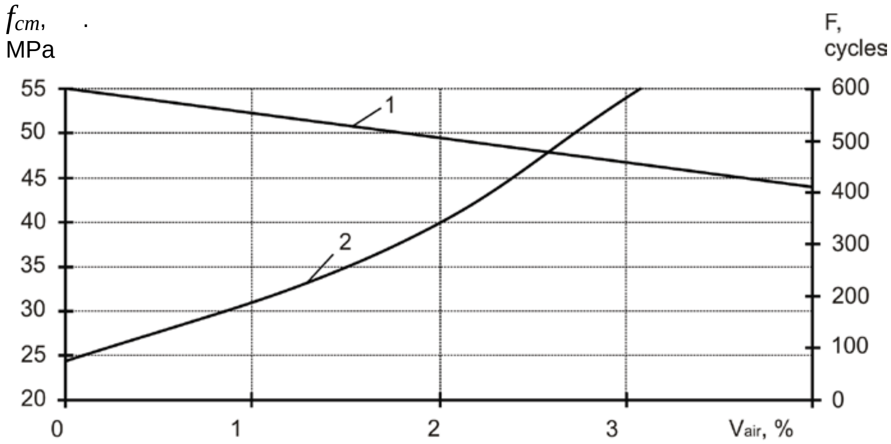

Figure 3. Dependence between the entrained air volume, concrete strength (f_{cm}) (*1*) and frost resistance (*F*) (2).

Note: concrete strength is calculated using a formula (14), concrete frost resistance (15).

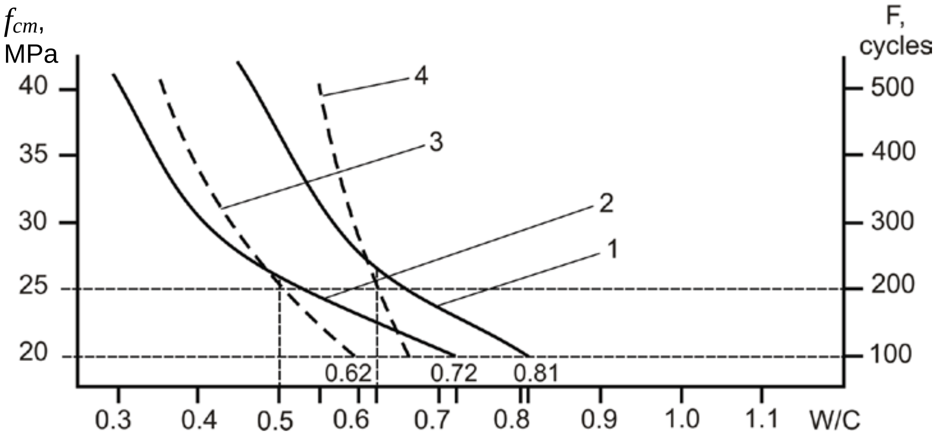

Figure 4. Relationship between *W/C* and given values of concrete strength (R_c) and frost resistance (*F*).

1 **– f_{cm} without entrained air; *2* – f_{cm} with 20 *l* of entrained air;**

3 **– *F* without entrained air; *4* – *F* with 20 *l* of entrained air.**

Example 1

Calculate the required values of the cement-water ratio (C/W), the volume of entrained air (V_{air}) and cement consumption to produce concrete with compressive strength at 28 days $f_{cm}^{28} = 30MPa$ and frost resistance F = 300 cycles. Apply Portland cement with compressive strength of 50 MPa, ordinary aggregates. Slump of the concrete mix – Sl = 1…4 cm.

1. According to the formula (16) we find the required volume of entrained air. The values of the coefficients A_1 and A_2 will be determined by the Table 2.

$$V_{air} = \frac{\ln\left(\frac{300}{0.34 \cdot 30^{1.68}}\right)}{0.35} = \frac{\ln(2.91)}{0.35} = 3.05\,\%\left(30.5\text{ l/m}^3\right).$$

2. Using the formula (14), taking the value of the coefficient A = 0.6 and the water consumption of 200 l/m^3 will determine the required value of C and C/W:

$$f_{cm} = 0.6 \cdot 50\left(\frac{C}{W + V_{air}} - 0.5\right);$$

$$C = \frac{\left(f_{cm} + 0.5AR_c\right)\left(W + V_{air}\right)}{AR_c} = \frac{(30 + 0.5 \cdot 0.6 \cdot 50)(200 + 30.5)}{0.6 \cdot 50} = 345.75\text{ kg/m}^3;$$

$$C/W = C:W = 345.75:200 = 1.73.$$

Lightweight Concrete. As known, for lightweight concrete on porous aggregates the water-cement ratio rule in its traditional formulation is unacceptable, as strength of such concrete is determined not just by cement stone density and accordingly strength, but also by strength and volumetric concentration of porous aggregates. Many formulas were suggested for calculating lightweight concrete strength [7]. Part of them characterized linear relation between concrete strength and cement consumption or C/W, considering the influence of mechanical and structural features of aggregates by generalized coefficients. Other formulas directly considered physic-mechanical parameters of porous aggregates, but were only indirectly related with composition parameters. These formulas require complicated calculations and provide approximate results.

Existing empirical formulas are of interest, mainly, for comparing materials based on various types of porous aggregates, but have low potential for concrete composition design. The existing practice of lightweight concrete composition design is based usually on using average tabulated data with subsequent experimental validation for given initial materials.

An integral parameter that takes into account both C/W and, indirectly, through pore volume of the aggregate, its strength, can be the parameter Z:

$$Z = \frac{V_{cem}}{V_w + (P_{ag} - W_{ab.ag})V_{ag} + V_{air}}, \tag{17}$$

were V_{cem}, V_w, V_{ag}, V_{air} are volumes of cement, water, aggregates and air, l/m^3;

P_{ag} is aggregate porosity,

$W_{ab.ag}$ is aggregate water absorption.

Claydite concrete compositions with compressive strength (f_{cm}) of 10...30 MPa at 28-days, density (ρ_c) of 1500...1800 kg/m^3 were calculated using recommendations given in [33] for claydite gravel with bulk density (ρ_{cl}^{b}) 600...800 kg/m^3 and water absorption ($W_{ab.cl}$) 0.18…0.22. Quartz sand was used as fine aggregate. The obtained results, presented in Table 3 and Figure 5, enable to approximate the dependence $R_c = f(Z)$ by a linear equation:

$$f_{cm} = AR_cZ, \tag{18}$$

where A = 1.7.

Experiments have confirmed the formula and accordingly the assumed physical preconditions (Table 4). The average strength deviation between experimental results and those calculated according Eq. (18) was 6 %.

Table 3. Calculation results for parameter Z and strength of claydite concrete.

No.	ρ_c, kg/m³	ρ_{cl}^{b}, kg/m³	W, kg/m³	V^{*}_{cl}, l/m³	$W_{ab.cl}^{vl}$	C, kg/m³	Z	f_{cm}, MPa	C/W
Claydite porosity P_{cl} = 0.4									
1	1500	800	197	507	0.22	230	0.257	17.50	1.17
2	1800	800	197	344	0.22	205	0.255	17.37	1.04
3	1500	800	197	507	0.22	320	0.358	24.35	1.62
4	1800	800	197	344	0.22	270	0.336	22.87	1.37
5	1600	800	197	468	0.22	380	0.436	29.64	1.93
6	1800	800	197	344	0.22	340	0.424	28.80	1.73
7	1600	800	197	468	0.22	450	0.516	35.10	2.28
8	1800	800	197	344	0.22	400	0.498	33.89	2.03
P_{cl} = 0.55									
9	1500	600	207	437	0.22	240	0.220	14.99	1.16
10	1800	600	207	274	0.22	210	0.228	15.49	1.01
11	1500	800	197	507	0.22	320	0.283	19.27	1.62
12	1800	500	212	252	0.18	300	0.317	21.56	1.42
13	1500	700	202	472	0.19	420	0.364	24.77	2.08
14	1800	600	207	274	0.22	360	0.390	26.55	1.74
15	1600	600	207	388	0.22	480	0.462	31.43	2.32
16	1800	700	202	300	0.19	420	0.437	29.72	2.08
P_{cl} = 0.7									
17	1500	800	197	507	0.22	230	0.168	11.46	1.17
18	1800	600	207	274	0.22	210	0.200	13.61	1.01
19	1500	600	207	437	0.22	340	0.263	17.90	1.64
20	1800	600	207	274	0.22	290	0.276	18.79	1.40
21	1500	800	197	507	0.22	400	0.293	19.93	2.03
22	1800	800	197	344	0.22	340	0.303	20.60	1.73
23	1500	800	197	507	0.22	470	0.344	23.41	2.39
24	1800	700	202	300	0.19	420	0.382	25.95	2.08

V^{*}_{cl} – volume of claydite gravel.

Table 4. Experimental and calculated values of claydite concrete strength.

No.	Calculated concrete strength, MPa	Concrete density, kg/m³	Materials consumptions, kg/m³			Volume of entrained air, %	Z	Experimental concrete strength, MPa
			cement	claydite	sand			
1	15	1500	224	$\frac{767}{800}$	479	3.2	0.222	15.1
2	15	1600	243	$\frac{440}{600}$	882	2.8	0.222	14.9
3	20	1500	369	$\frac{380}{500}$	691	2.7	0.296	19.8
4	20	1600	289	$\frac{708}{800}$	563	2.3	0.296	19.8
5	30	1600	477	$\frac{572}{700}$	477	2.1	0.445	29.4
6	30	1800	392	$\frac{520}{800}$	835	1.8	0.445	30.1

Notes: 1. Denominator shows the bulk density of claydite (Cl). 2. Slump for all compositions was 5 cm, 28-day strength of cement was 40 MPa.

From equations (18) and (19) it can be found that when is used for lightweight concrete, dense sand without air-entraining additives cement consumption:

$$V_{cem} = \frac{f_{cm}\left(V_w + (P_{ag} - W_{ab.ag})V_{ag} + V_{air}\right)}{AR_{\text{ц}}}; \tag{19}$$

$$C = V_{cem}\rho_{cem}, \tag{20}$$

were ρ_{cem} – density of cement ($\rho_{cem} \approx 3.1$).

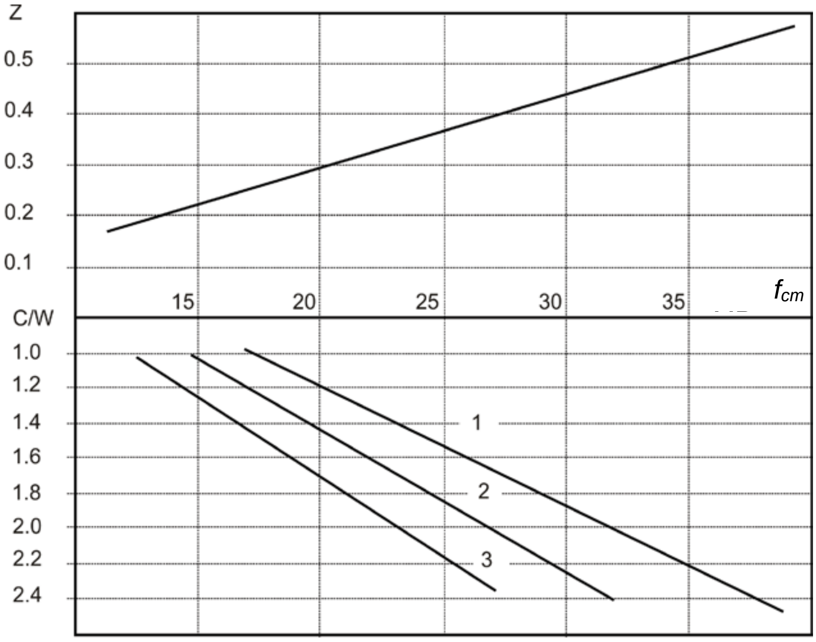

Figure 5. Dependence of claydite concrete strength (f_{cm}) on C/W and parameter Z: *1* – claydite porosity is 0.4; *2* – 0.55; *3* – 0.7.

Using parameter Z in formula for lightweight concrete strength enables to propose rather simple its composition design method.

Example 2

Determine the consumption of cement to obtain claydite concrete with a strength 25 MPa and a density of 1700 kg/m^3 on claydite gravel with a bulk density of ρ^b_{cl} = 700 kg/m^3 and quartz sand. The slump of the mixture Sl = 5 cm. The strength of cement R_{cem} = 50 MPa. Intergranular hollowness of claydite P^0_{cl} = 0.44. Claydite porosity P_{cl} = 53 %, water absorption $W_{ab.cl}$ = 20 %, V_{air} = 15 l/m^3.

1. Determine the desired “modified C/W” (parameter Z) to ensure the specified strength of concrete from the formula (17):

$$Z = \frac{25}{1.7 \cdot 50} = 0.294.$$

2. Determine the required water content to achieve the desired workability of the concrete mixture according to the empirical formula [1, 6]:

$$W = 2.33Sl - 0.04\rho_{cl} + 230;$$

$$W = 2.33 \cdot 5 - 0.04 \cdot 700 + 230 = 214 \text{ l/m}^3.$$

3. Calculate the volume concentration of φ and the volume content of V_{cl} the claydite gravel in concrete, using the formula:

$$\varphi = 1 - P^0_{cl}\alpha,$$

$$V_\alpha = 1000\varphi,$$

were α – coefficient of moving apart of coarse aggregate grains by cement-sand mortar (according to reference data [1] for concrete with a density of ρ_c = 1700 and a bulk density of claydite ρ^b_{cl} = 700, α = 1.45).

$$\varphi = 1 - 0.44 \cdot 1.45 = 0.362.$$

Craydite consumption:

$$V_{cl} = 1000 \cdot 0.362 = 362 \text{ l/m}^3.$$

4. Cement consumption is found by the formulas (19), (20)

$$V_{cem} = 0.294 \cdot (214 + (0.53 - 0.2) \cdot 362) + 15 = 113 \text{ l/m}^3;$$

$$C = 113 \cdot 3.1 = 350.3 \text{ kg/m}^3.$$

4. Conclusions

1. Modifying C/W taking into account of the influence of entrained air allows to correct of the strength of concrete calculated dependence that can be used for design concrete compositions with normalized values of concrete compressive strength under compression and frost resistance.

For light concrete, modifying C/W is advisable in view of the air volume contained in the pores of the porous aggregate. Using the proposed parameter Z, it is possible to calculate the composition of light weight concretes, taking into account the influence of both the cement-water ratio and the porosity of the aggregates.

References

1. Dvorkin, L., Dvorkin, O. Basics of concrete science: optimum design of concrete mixtures. Saint-Peterburg: Amason (Kindle edition) Stroi-Beton, 2006. 692 p.
2. Brandt, M. Optimization Methods for Material Design of Cement – Based Compozites. CRC Press. Roca Raton, 2014. 328 p. [Online]. URL: https://www.crcpress.com/Optimization-Methods-for-Material-Design-of-Cement-based-Composites/Brandt/p/book/9780419217909
3. Larrard, F. Concrete mixture – proportioning a scientific approach. CRC Press, London, 1999. 448 p. [Online]. URL: https://epdf.tips/queue/concrete-mixture-proportioning-a-scientific-approach.html
4. Kosmatka, S., Kerkhoff, B. Panarese, W. Design and Control of Concrete Mixture. 14th Edition. PSA, Skokie, Illinois, 2014. 358 p. [Online]. URL: https://www.researchgate.net/profile/Steven_Kosmatka/publication/284663491_Design_and_Control_of_Concrete_Mixtures/links/5655d8f908aefe619b1c5f2b/Design-and-Control-of-Concrete-Mixtures.pdf
5. Sonebi, M., Bassuoni, M., Yahia, A. Previous Concrete: Mix Design, Properties and Applications. RILEM Technical Letters, l, 2016. Pp. 109–115 [Online]. URL: http://dx.doi.org/10.21809/rilemtechlett.2016.24
6. Bazhenov, Yu.M., Demyanova, V.S., Kalashnikov, V.I. Modifitsirovannyye vysokokachestvennyye betony [Modified high-quality concretes] M.: Izdatelstvo: Assotsiatsiya stroitelnykh VUZov, 2006. 368 s. [Online]. URL: http://mirknig.su/knigi/stroitelstvo_i_remont/110641-modificirovannye-vysokokachestvennye-betony.html (rus)
7. Dvorkin, L., Dvorkin, O., Ribakov, Y. Multi-Parametric Concrete Compositions Design. Nova Science Publishers, Inc. New York, 2013. 223 p. [Online]. URL: https://www.bookdepository.com/Multi-Parametric-Concrete-Compositions-Design-Leonid-Dvorkin/9781624179112
8. Design and Control of Concrete Mixtures. 15th edition, Portland Cement Association. 2011. 460 p. [Online]. URL: https://faculty.uml.edu/ehajduk/Teaching/14.310/documents/EB001.15.pdf
9. Kett, l. Engineered Concrete Mix Design and Test Methods. 2th Edition 2009. CRC Press, 264 p. [Online]. URL: https://www.crcpress.com/Engineered-Concrete-Mix-Design-and-Test-Methods-Second-Edition/Kett/p/book/9781420091014
10. Day, K. Concrete Mix Design. Quality Control and Specification. 4th Edition 2017. CRC Press, 349 p. [Online]. URL: https://www.crcpress.com/Concrete-Mix-Design-Quality-Control-and-Specification/Day-Aldred-Hudson/p/book/9781138073531
11. Sabnis Cement Concrete Mix – Design Principles &Practice with CD. 6th Edition. 2017. V.Prakashan. 422 p.
12. Neville, A. Properties of concrete. 5-th edition 2011. Wiley, 620 p [Online]. URL: https://igitgeotech.files.wordpress.com/2014/10/properties-of-concrete-by-a-m-neville.pdf
13. Popovics, S, Contribution to the concrete strength versus water-cement ratio relationship. Mater. Civil. Eng., 2008, 20, Pp. 459–463. DOI: 10.1061/(ASCE)0899-1561(2008)20:7(459).
14. Dvorkin, L., Dvorkin, O., Ribakov, Y. Mathematical experiments planning in concrete technology. Nova Science Publishers, New York, 2012. 173 p. [Online]. URL: https://www.researchgate.net/publication/293205467_Mathematical_experiments_planning_in_concrete_technology
15. Kheder G., Gabhan A., Suhad Mathematical model for the prediction of cement compressive strength of the ages of 7 and 28 days. Mater. Struct., 36, 2003. Pp.693-701 [DOI:10.1007/BF02479504].
16. Hwang, K., Noguchi, T., Tomosava, F. Prediction model of compressive strength of fly-ash concrete. Cement Concrete Res., 34, 2004. Pp. 2269–2276. [Online]. URL: ftp://ftp.ecn.purdue.edu/olek/PTanikela/To%20Prof.%20Olek/Data/Strength%20Activity%20Index/INFORMATION/strength%20as%20a%20function%20of%20blaines.pdf
17. Hamid-Zaden, N., Jamili, A., Nariman-Zadeh, A., Akbar-Zadeh. A polynomial model for concrete compressive strength prediction using GMDH – type neural networks and genetic algorithem. Proceedings of the 5th International Conference of System Science, Canary Islands, Spain, 2006. Pp. 16–18. [Online]. URL: https://www.researchgate.net/publication/254457742_A_Polynomial_Model_for_Concrete_Compressive_Strength_Prediction_using_GMDH-type_Neural_Networks_and_Genetic_Algorithm
18. Zain, M., Abd, S. Multiple regression model for compressive strength prediction of high performance concrete. J. Applied Sci. 2009. No. 9. Pp. 155–160. DOI: 10.3923/jas.2009.155.160
19. Saadoon, T., Gomes-Meijide B., Garcia A. New predictive methodology for the apparent activation energy and strength of conventional and rapid hardening concretes. Cement and Concrete Research. January 2019. Vol. 115. Pp. 264–273. DOI: 10.1016/j.cemconres.2018.10.020.
20. DeRousseau, M., Kaspzyk, J., Srubar, W. Computational design optimization of concrete mixtures: A revier Cement and Concrete Reseach. Vol. 109. 2018. Pp. 42–53. [Online]. URL: https://doi.org/10.1016/j.cemconres.2018.04.007
21. Mayercsik, N., Vandamme, M., Kurtis, K. Asessing the efficiency of entrained air voids for freeze-thaw durability through modeling. Cement and Concrete research. 2016. Vol. 88. Pp. 43–59. DOI: 10.1016/j.cemconres.2016.06.004.
22. Jiao, D., Shi, C., Yuan, Q., An, X., Liu, Yu. Mixture design of concrete using simplex centroid design method. Cement and Concrete Composites. 2018. Vol. 89. Pp. 76–88. DOI: 10.17632/xhss7xv6wz.1.
23. Dvorkin, L., Zhitkovsky, V., Stepasiuk, Y. A method for design of high strength concrete composition considering curing temperature and duration. Construction and Building Materials. 2018. Vol. 186. Pp. 731–739. DOI: 10.1016/j.conbuildmat.2018.08.014.
24. Larsen, O.A., Narut, V.V. Samouplotnyayushchiysya beton s karbonatnym napolnitelem dlya obyektov transportnoy infrastruktury [Self-compacting concrete with limestone powder for transport infrastructure]. Inzhenerno-stroitelnyy zhurnal. 2016. № 8(68). S. 76–85. DOI: 10.5862/MCE.68.8. (rus)

25. Dvorkin, L., Zhitkovsky V., Ribakov Y. Concrete and mortar production using stone siftings, 2018, CRC Press, Roca Raton, London, New York. 155 p.

26. Furmanov, N.Ye. Blagopriyatnyy sostav betona dlya izgotovleniya vodonepronitsayemykh konstruktsiy po sisteme «Belaya vanna» [The favorable composition of concrete for the manufacture of waterproof structures using the «White Bath» system]. Inzhenerno-stroitelnyy zhurnal. 2009. № 3 (5). C. 11–16. [Online]. URL: http://engstroy.spbstu.ru/index_2009_03/furmanov_gidroizoliaciya.pdf (rus)

27. Barabanshchikov, Yu.G., Belyayeva, S.V., Arkhipov, I.Ye., Antonova, M.V, Shkolnikova, A.A, Lebedeva, K.S. Vliyaniye superplastifikatorov na svoystva betonnoy smesi [Influence of superplasticizers on the concrete mix properties]. Inzhenerno-stroitelnyy zhurnal. 2017. № 6(74). S. 140–146. DOI: 10.18720/MCE.74.11. (rus)

28. Hedegaord, S., Hansen, T. Modified water/cement ratio law for compressive strength of fly ash concretes. Materials and Structure. 1992. Vol. 25. Pp. 273–283. DOI: 10.1007/BF02472668.

29. Abdulahi, M., Ojeade G. Modified water-cement ratio law for compressive strength of rice husk ash concrete. Nigerian Journal of Technology. 2017. Vol. 36. No. 2. Pp. 373–379. DOI:10.4314/njt.v36i2.8.

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Модифицированное правило водоцементного соотношения для проектирования бетонов, содержащих воздух

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Ключевые слова: Модифицированное Ц/В; объем вовлеченного воздуха; расход цемента; прочность и морозостойкость бетона; объем пор заполнителя; состав легких бетонов.

Аннотация. Проектирование составов бетона, содержащего вовлеченный воздух, обычно выполняется с помощью эмпирических подборов, что является довольно трудоемким и длительным процессом. В статье экспериментально обоснованы расчетные формулы с помощью правила модифицированного Ц/В, которое основано на известных эмпирических зависимостях и позволяет находить содержание компонентов бетона с заданными параметрами прочности, морозостойкости и плотности. Приведены результаты экспериментальных исследований, выполненных с помощью компрессионного метода определения объема вовлеченного воздуха, а также стандартных методов определения прочности и морозостойкости бетона. Полученные формулы проверены на примерах расчета составов тяжелого бетона с заданной прочностью и морозостойкостью и конструкционного керамзитобетона с заданными значениями прочности и плотности.

Литература

1. Dvorkin L., Dvorkin O. Basics of concrete science: optimum design of concrete mixtures. Saint-Peterburg: Amason (Kindle edition) Stroi-Beton, 2006. 692 p.
2. Brandt M. Optimization Methods for Material Design of Cement – Based Compozites. CRC Press. Roca Raton, 2014. 328 p. [Электронный ресурс]. URL: https://www.crcpress.com/Optimization-Methods-for-Material-Design-of-Cement-based-Composites/Brandt/p/book/9780419217909
3. Larrard F. Concrete mixture – proportioning a scientific approach. CRC Press, London, 1999. 448 p. [Электронный ресурс]. URL: https://epdf.tips/queue/concrete-mixture-proportioning-a-scientific-approach.html
4. Kosmatka S., Kerkhoff B. Panarese W. Design and Control of Concrete Mixture. 14th Edition. PSA, Skokie, Illinois, 2014. 358 p. [Электронный ресурс]. URL: https://www.researchgate.net/profile/Steven_Kosmatka/publication/284663491_Design_and_Control_of_Concrete_Mixtures/links/5655d8f908aefe619b1c5f2b/Design-and-Control-of-Concrete-Mixtures.pdf
5. Sonebi M., Bassuoni M., Yahia A. Previous Concrete: Mix Design, Properties and Applications. RILEM Technical Letters, I, 2016. Pp. 109-115. [http://dx.doi.org/10.21809/rilemtechlett.2016.24
6. Баженов Ю.М., Демьянова В.С., Калашников В.И. Модифицированные высококачественные бетоны [Modified high-quality concretes] М.: Изд-во: Ассоциация строительных ВУЗов, 2006. 368 с. [Электронный ресурс]. URL: http://mirknig.su/knigi/stroitelstvo_i_remont/110641-modificirovannye-vysokokachestvennye-betony.html
7. Dvorkin L., Dvorkin O., Ribakov Y. Multi-Parametric Concrete Compositions Design. Nova Science Publishers, Inc. New York, 2013. 223 p. [Электронный ресурс]. URL: https://www.bookdepository.com/Multi-Parametric-Concrete-Compositions-Design-Leonid-Dvorkin/9781624179112
8. Design and Control of Concrete Mixtures. 15th edition, Portland Cement Association. 2011. 460 p. [Электронный ресурс]. URL: https://faculty.uml.edu/ehajduk/Teaching/14.310/documents/EB001.15.pdf
9. Kett I. Engineered Concrete Mix Design and Test Methods. 2th Edition 2009. CRC Press, 264 p. [Электронный ресурс]. URL: https://www.crcpress.com/Engineered-Concrete-Mix-Design-and-Test-Methods-Second-Edition/Kett/p/book/9781420091014
10. Day K. Concrete Mix Design. Quality Control and Specification. 4th Edition 2017. CRC Press, 349 p. [Электронный ресурс]. URL: https://www.crcpress.com/Concrete-Mix-Design-Quality-Control-and-Specification/Day-Aldred-Hudson/p/book/9781138073531
11. Sabnis Cement Concrete Mix – Design Principles &Practice with CD. 6th Edition. 2017. V. Prakashan. 422 p.
12. Neville A. Properties of concrete. 5-th edition 2011. Wiley, 620 p. [Электронный ресурс]. URL: https://igitgeotech.files.wordpress.com/2014/10/properties-of-concrete-by-a-m-neville.pdf
13. Popovics S. Contribution to the concrete strength versus water-cement ratio relationship // Mater. Civil. Eng. 2008. No. 20. Pp. 459–463. DOI: 10.1061/(ASCE)0899-1561(2008)20:7(459).

14. Dvorkin L., Dvorkin O., Ribakov Y. Mathematical experiments planning in concrete technology. Nova Science Publishers, New York, 2012. 173 p. [Электронный ресурс]. URL: https://www.researchgate.net/publication/293205467_Mathematical_experiments_planning_in_concrete_technology
15. Kheder G., Gabhan A., Suhad Mathematical model for the prediction of cement compressive strength of the ages of 7 and 28 days // Mater. Struct. 2003. No. 36. Pp. 693–701. DOI: 10.1007/BF02479504.
16. Hwang K., Noguchi T. and Tomosava F. Prediction model of compressive strength of fly-ash concrete // Cement Concrete Res. 2004. No. 34, Pp. 2269–2276. [Электронный ресурс]. URL: ftp://ftp.ecn.purdue.edu/olek/PTanikela/To%20Prof.%20Olek/Data/Strength%20Activity%20Index/INFORMATION/strength%20as%20a%20function%20of%20blaines.pdf
17. Hamid-Zaden N., Jamili A., Narim-Zadeh A., Akbar-Zadeh. A polynomial model for concrete compressive strength prediction using GMDH – type neural networks and genetic algorithem. Proceedings of the 5th International Conference of System Science, Canary Islands, Spain, 2006. Pp. 16–18. [Электронный ресурс]. URL: https://www.researchgate.net/publication/254457742_A_Polynomial_Model_for_Concrete_Compressive_Strength_Prediction_using_GMDH-type_Neural_Networks_and_Genetic_Algorithm
18. Zain M., Abd S. Multiple regression model for compressive strength prediction of high performance concrete // J. Applied Sci. 2009. No. 9. Pp. 155–160. DOI: 10.3923/jas.2009.155.160.
19. Saadoon T., Gomes-Meijide B., Garcia A. New predictive methodology for the apparent activation energy and strength of conventional and rapid hardening concretes // Cement and Concrete Research. January 2019. Vol. 115. Pp. 264–273. DOI: 10.1016/j.cemconres.2018.10.020.
20. DeRousseau M., Kaspzyk J., Srubar W. Computational design optimization of concrete mixtures: A revier // Cement and Concrete Reseach. Vol. 109. 2018. Pp. 42–53 [Электронный ресурс]. URL: https://doi.org/10.1016/j.cemconres.2018.04.007
21. Mayercsik N., Vandamme M., Kurtis K. Asessing the efficiency of entrained air voids for freeze-thaw durability through modeling // Cement and Concrete research. 2016. Vol 88. Pp. 43–59. DOI: 10.1016/j.cemconres.2016.06.004.
22. Jiao D., Shi C., Yuan Q., An X., Liu Yu. Mixture design of concrete using simplex centroid design method // Cement and Concrete Composites. 2018. Vol. 89. Pp. 76–88. DOI: 10.17632/xhss7xv6wz.1.
23. Dvorkin L., Zhitkovsky V., Stepasiuk Y. A method for design of high strength concrete composition considering curing temperature and duration // Construction and Building Materials. 2018. Vol. 186. Pp. 731–739. DOI: 10.1016/j.conbuildmat.2018.08.014.
24. Ларсен О.А., Наруть В.В. Самоуплотняющийся бетон с карбонатным наполнителем для объектов транспортной инфраструктуры // Инженерно-строительный журнал. 2016. № 8(68). С. 76–85. DOI: 10.5862/MCE.68.8.
25. Dvorkin L., Zhitkovsky V., Ribakov Y. Concrete and mortar production using stone siftings, 2018, CRC Press, Roca Raton, London, New York, 155 p.
26. Фурманов Н.Е. Благоприятный состав бетона для изготовления водонепроницаемых конструкций по системе «Белая ванна» // Инженерно-строительный журнал. 2009. № 3 (5). С. 11–16 [Электронный ресурс]. URL: http://engstroy.spbstu.ru/index_2009_03/furmanov_gidroizoliaciya.pdf
27. Барабанщиков Ю.Г., Беляева С.В., Архипов И.Е., Антонова М.В, Школьникова А.А, Лебедева К.С. Влияние суперпластификаторов на свойства бетонной смеси [Influence of superplasticizers on the concrete mix properties] // Инженерно-строительный журнал. 2017. № 6(74). С. 140–146. DOI: 10.18720/MCE.74.11.
28. Hedegaord S., Hansen T. Modified water/cement ratio law for compressive strength of fly ash concretes // Materials and Structure. 1992. Vol 25. Pp. 273–283. DOI: 10.1007/BF02472668.
29. Abdulahi M., Ojeade G. Modified water-cement ratio law for compressive strength of rice husk ash concrete // Nigerian Journal of Technology. 2017. Vol. 36, No. 2. Pp. 373–379. DOI: 10.4314/njt.v36i2.8.

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